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CRITICAL REVIEW OF CAPACITIVE DEIONIZATION: DESIGN, OPERATION CONSIDERATION AND REAL-WORLD ENVIRONMENTAL APPLICATIONS

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Abstract

Capacitive Deionization (CDI) has emerged as a promising and environmentally sound solution for addressing pressing water treatment challenges. This critical review meticulously examines the design, operational considerations, and performance metrics of CDI systems, particularly highlighting their significance in environmental applications under real-world conditions for handling different water sources such as groundwater, surface water, sea water. Various CDI configurations, electrode materials, and operational parameters are scrutinized through an extensive analysis of literature, with their direct influence on system efficiency, ion removal capacities, and long-term stability being elucidated. The reduced energy consumption, minimal chemical usage, and potential for sustainable water treatment of CDI, as compared to traditional methods, are emphasized from an environmental perspective. Moreover, this review underscores the pivotal role of CDI in practical environmental applications, including desalination, wastewater treatment, and remediation of inorganic pollutants (heavy metals and hardness) and resource recovery (nutrient, uranium, lithium, . . .). By presenting compelling case studies, CDI's efficacy in mitigating environmental impacts is illustrated, offering a cleaner and more cost-effective alternative to conventional treatment methods. By outlining challenges and charting future directions, this review serves as a roadmap for researchers, engineers, and policymakers, facilitating the development of sustainable and efficient water treatment strategies. In an era marked by escalating environmental concerns, CDI emerges as a potential technology for responsible and effective water management, poised to shape a more sustainable future.

Keywords: capacitive deionization; desalination; wastewater treatment; heavy metal removal; hardness removal; resource recovery.

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1. Introduction

In an era defined by mounting concerns over water scarcity and contamination, the quest for efficient and sustainable water purification technologies has taken center stage. Among these innovations, capacitive deionization (CDI) stands out as a promising solution [1, 2]. As the world seeks dependable methods to secure access to clean water, our exploration of CDI's potential is both timely and pivotal. In a world confronted by escalating concerns regarding the scarcity and contamination of water resources, the imperative for effective and sustainable water treatment technologies has become increasingly pronounced. Population growth, industrialization, and environmental stressors have placed unprecedented demands on our ability to provide safe and potable water. With nearly 1.1 billion people lacking access to clean drinking water and pollution jeopardizing aquatic ecosystems, the urgency to address these challenges is evident [3]. In response, a myriad of water purification technologies have emerged, each aiming to mitigate the adverse impacts of water scarcity and pollution. Among

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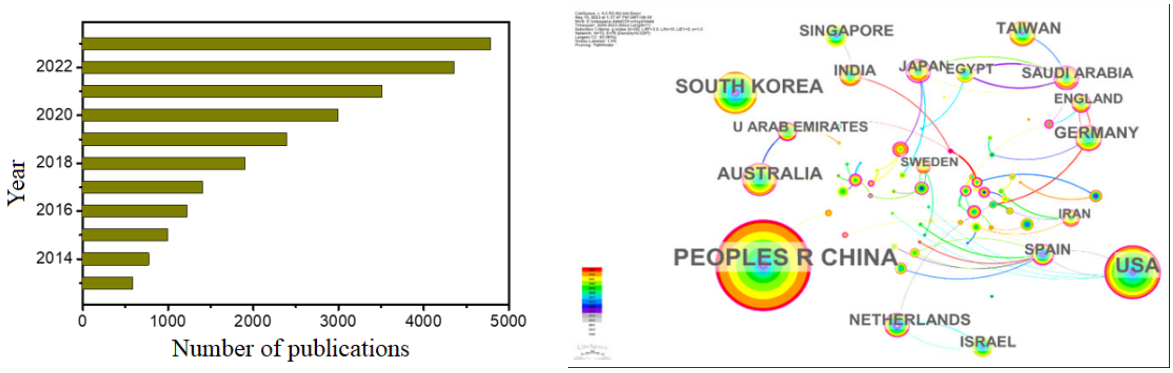
these, CDI offers a unique approach, harnessing electrochemical principles to remove ions and impurities from water. In this context, our review paper endeavors to explore CDI comprehensively, with a specific focus on its design configurations, performance metrics, and environmental sustainability, as it contributes to the collective pursuit of a solution to one of the most pressing global issues of our time [1, 4].

CDI emerges as a groundbreaking technology with immense potential to revolutionize water purification strategies. Research related to CDI technology has been significantly gaining traction among scientists, with the number of publications consistently rising from 2013 to 2023, as indicated by data collected from Web of Science (Fig. 1(a)). In Fig. 1(b), the expansive global collaboration networks dedicated to CDI are depicted, highlighting the worldwide prevalence of this condition. Notably, robust research endeavors pertaining to CDI are evident in the number of papers in various nations during the period 2009 to 2023, including China (1082), the United States (406), South Korea (278), Germany (103), and Taiwan (98) [5]. CDI stands as a distinct electrochemical approach designed to selectively and efficiently remove ions and impurities from water. This process relies on the principles of electrostatic attraction, where oppositely charged electrodes, typically composed of porous carbon materials, attract and capture ions from the water. The innovative aspect of CDI lies in its energy-efficient and reversible operation, as it leverages electric fields to adsorb ions during charging and release them during discharging cycles. This unique mechanism offers an environmentally sustainable alternative to conventional ion exchange and adsorption methods, opening doors to the possibility of high-capacity, low-energy water purification. As our journey through this review is embarked upon, the intricacies of CDI are delved into, unraveling its potential applications and critically assessing its performance in real-world scenarios [5, 6].

The impetus behind this review stems from the pressing need to comprehensively assess CDI as a pivotal technology in the realm of water purification. As the global demand for clean water escalates in the face of mounting population growth and environmental challenges, efficient and sustainable water treatment solutions have become an urgent requirement [7]. While CDI exhibits substantial promise in this context, a nuanced and in-depth examination is needed. Existing research, though valuable, often focuses on specific aspects of CDI, such as electrode materials or performance metrics, and lacks a comprehensive, integrated perspective. Furthermore, in the rapidly evolving field of CDI, numerous recent studies have introduced innovative design configurations and applications that require thorough evaluation. Our review paper aims to bridge these gaps by consolidating and critically evaluating the existing body of knowledge concerning CDI, highlighting its design configurations, performance metrics, and environmental implications. By doing so, the need for a more comprehensive understanding of the technology is addressed, which can guide more informed decision-making, future research, and successful implementation in real-world scenarios. This review paper assumes a pivotal role in elucidating the feasibility of CDI in real-world applications and its role in addressing one of the most critical global issues of our time. The overarching objective of this review paper is to provide a comprehensive assessment of CDI as a technology for water purification and its potential for real-world applications. To achieve this, a detailed examination of CDI design configurations, performance metrics, and its environmental impact will be undertaken. The primary focus is to identify the strengths and limitations of various CDI approaches, evaluating their effectiveness in addressing water purification challenges. Furthermore, the findings from existing literature will be synthesized to offer a well-rounded perspective on CDI and its relevance in practical scenarios. By the end of this review, light is sought to be shed on the multifaceted nature of CDI technology, offering insights into its real-world applicability and guiding further research in this vital domain.



(a) The number of related publications in CDI

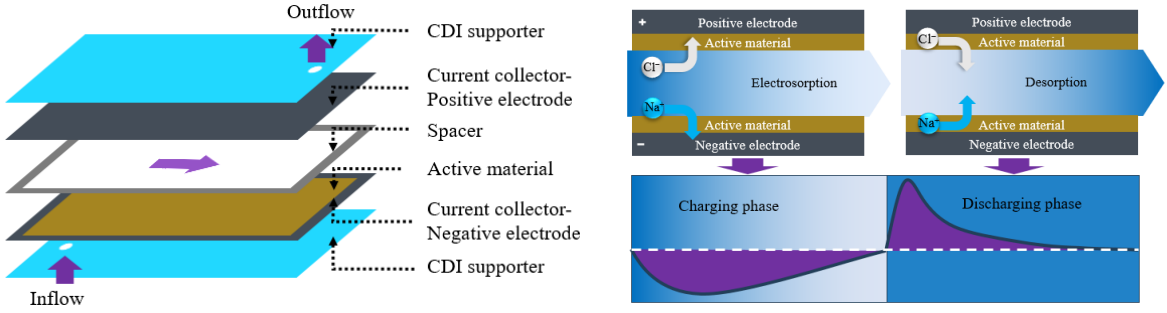
(b) National collaboration networks related to CDI

Figure 1. Statistics of the number of scientific publications from 2013 to 2023 and national collaboration networks related to CDI (reproduced with permission) [5]

2. Literature in the CDI field

2.1. Principles and working mechanisms

CDI is an innovative and environmentally friendly technique for the removal of ionic impurities from water. At its core, CDI operates on the fundamental principles of electrochemistry and relies on the electrical double layer phenomenon, where ions accumulate at the interface of the electrolyte and electrode due to their electrical potential. In 1883, Helmholtz proposed that the distribution of charges in capacitors at the electrical double layer is governed by the presence of charged species on the electrode's surface, while oppositely charged ions are present in the surrounding solution. This double layer can be divided into two regions, as suggested by the Gouy-Chapman-Stern model: the inner area, referred to as the Helmholtz surface, where ions entirely cover the electrode surface, and the outer region, known as the Gouy-Chapman layer or diffusion layer, which extends beyond the surface. The distribution of charges from the surface is influenced by the surface potential [6].



(a) CDI structure

(b) CDI working mechanism

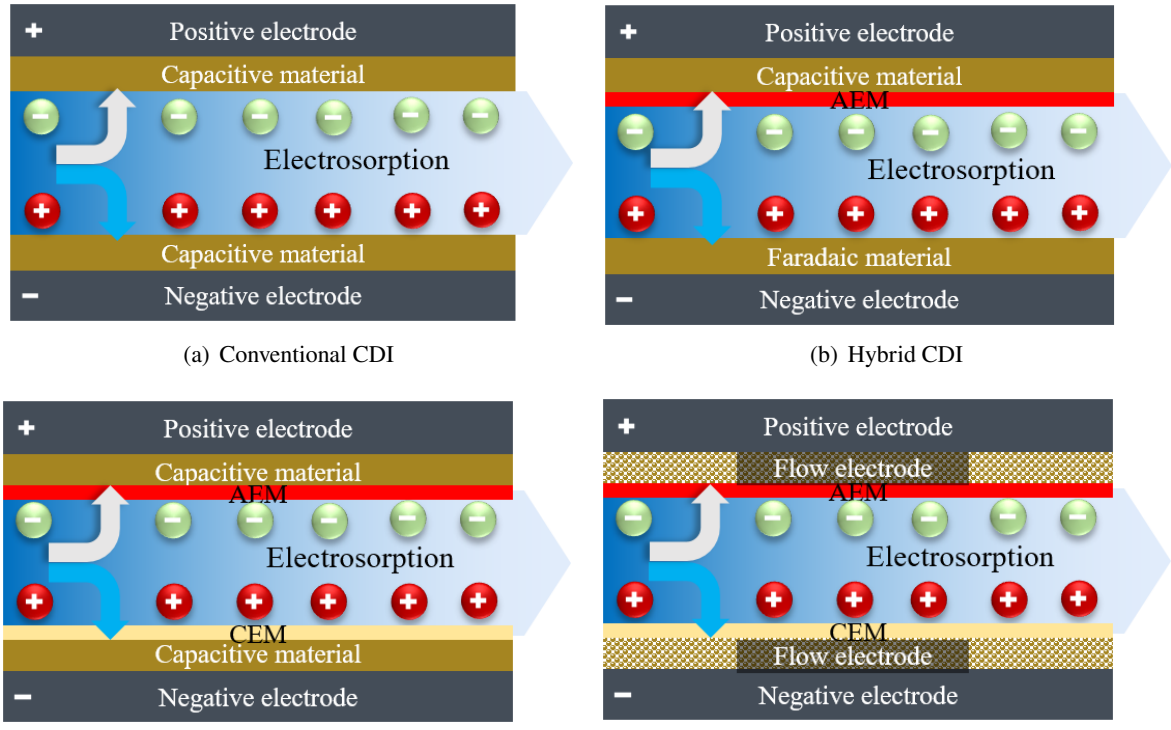
Figure 2. Schematic diagram and operation mechanism of a basic CDI module

The central component in the application of CDI technology is the CDI module, which plays a crucial role in electrochemically extracting ions from aqueous solutions. Carefully crafted, the CDI cell is designed for optimal deionization efficiency, incorporating alternating layers of porous electrodes, current collectors, spacers, and frame supporters (Fig. 2(a)). Fig. 2(b) shows the working mechanism and the change of salt concentration by the time in a cycle of CDI. When a voltage is

applied across these electrodes, ions in the water are attracted to their respective charged surfaces, effectively adhering to the electrode materials. Subsequently, the removal of ions from the water occurs as they accumulate on the electrodes. During the regeneration phase, the electric potential is reversed, causing the ions to be released back into a separate compartment, leaving behind purified water. One of the key advantages of CDI is its energy efficiency, as it does not require the use of chemicals or high-pressure systems, making it an eco-friendly and cost-effective alternative for desalination and water purification. Furthermore, the technology offers the potential for customization by varying the electrode materials and other operational parameters, making it a versatile solution for a wide range of water treatment applications [8].

2.2. *Capacitive deionization configuration*

CDI stands at the forefront of innovative technologies addressing water treatment challenges, with its success hinging on nuanced configurations tailored to specific applications. Within the realm of CDI, various configurations have emerged, each offering distinctive advantages and considerations (Fig. 3(a)) [7, 9]. Hybrid capacitive deionization (HCDI), integrating the strengths of multiple deionization approaches, presents a promising avenue for enhanced ion removal efficiency (Fig. 3(b)) [10, 11]. Membrane capacitive deionization (MCDI) introduces a spatial separation, augmenting selectivity and expanding the application spectrum (Fig. 3(c)) [12, 13]. Flow capacitive deionization (FCDI), a dynamic variation, leverages fluid dynamics to optimize ion removal rates, exemplifying the adaptability of CDI configurations in meeting diverse real-world challenges (Fig. 3(d)) [14, 15].



(a) Conventional CDI

(b) Hybrid CDI

(c) Membrane CDI

(d) Flow CDI

Figure 3. Various cell architectures of capacitive deionization

Upon scrutinizing fluid velocity profiles in the electrode area, as investigated by Lado et al., distinct patterns emerge (Fig. 4). The A pattern reveals heightened velocity vectors near the chamber

entrance, while configurations (B) and (F) result in significant vectors beyond the entrance and output zones, potentially hindering electrode efficiency. In contrast, flow frame structures with dots or perforated channels arranged horizontally (geometries (C), (D), and (E)) showcase a more favorable outcome, fostering an even flow distribution across the entire electrode area. Streamlines for these designs exhibit uniform velocity profiles, devoid of dead zones or undesirable phenomena. A redesign of the opening, increasing small entries along the flow frame's width, proves crucial for achieving an even flow distribution. This enhancement is vital for effective electric charge utilization during deionization, facilitating ion transport from bulk to electrode surface. Considering these factors, the flow frame design in pattern D emerges as the most suitable choice and has been selected for stack construction [16].

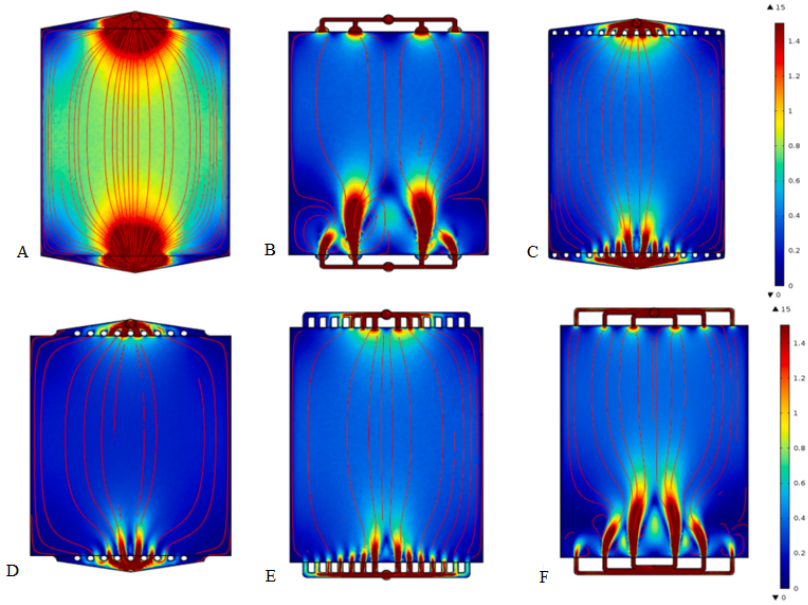


Figure 4. Simulating geometry and the fluid flow path of distinct CDI patterns (reproduced with permission) [16]

2.3. Electrode materials

CDI relies on efficient electrode materials for the removal of ions from water. The electrodes used fall into two main categories: Electric double layer capacitor (EDLC) and pseudocapacitor electrodes. EDLC electrodes, like active carbon [7], mesoporous carbon [17], hierarchically porous carbon [18], graphene and carbon nanotubes [19], are renowned for their high specific surface area and porosity (Fig. 5) These characteristics enable a large electrochemically active area, providing ample space for ions to adsorb onto the surface. The mechanism involves the formation of an electric double layer with non-Faradic reaction at the electrode-electrolyte interface, allowing for efficient ion capture and release during the CDI process. However, while EDLC electrodes excel in ion adsorption due to their high surface area, their specific capacitance might be lower compared to pseudocapacitors [20, 21]. It is noteworthy that a majority of contemporary research in CDI applications under actual conditions predominantly employs porous activated carbon materials. The preference for these materials is attributed to their cost-effectiveness and stable performance characteristics [1, 7].

On the other hand, pseudocapacitor electrodes with Faradic reactions encompass materials like metal/metallic compounds (e.g., TiO_2, MnO_2, CeO_2, ...) [9, 22], heteroatom-doped carbonaceous materials (e.g., oxygen, nitrogen, sulfur, ...) [23], Mxene [24], and Prussian blue analogues [25] (Fig. 5).

These materials exhibit pseudocapacitive behavior, involving reversible and fast faradaic reactions that store and release charge. Pseudocapacitors often demonstrate higher specific capacitance than EDLC electrodes due to their ability to store charge via redox reactions, offering potentially higher energy storage capacities. As outlined by Zhang et al., Faradic reactions are categorized into three distinct groups. Group I comprises oxidation processes that occur at the anode, encompassing reactions like carbon electrode oxidation, chloride oxidation, water oxidation, and specific contaminant oxidations such as those of inorganic ions and organic substances. Group II involves reduction processes occurring at the cathode, with oxygen reduction being predominant. Group III encompasses Faradaic ion storage mechanisms where pseudocapacitive/ intercalation effects facilitate the reversible redox reactions for ion storage, as opposed to electrostatic storage in the EDLs at the electrode/electrolyte interfaces [26].

The selection of electrode material in CDI depends on several factors including specific performance requirements such as energy efficiency, charge storage capacity, cycling stability, and cost-effectiveness. EDLC electrodes, with their exceptional surface properties, are well-suited for high-efficiency ion adsorption, whereas pseudocapacitor materials offer potential for higher energy storage but might have different trade-offs in terms of cost or stability [27].

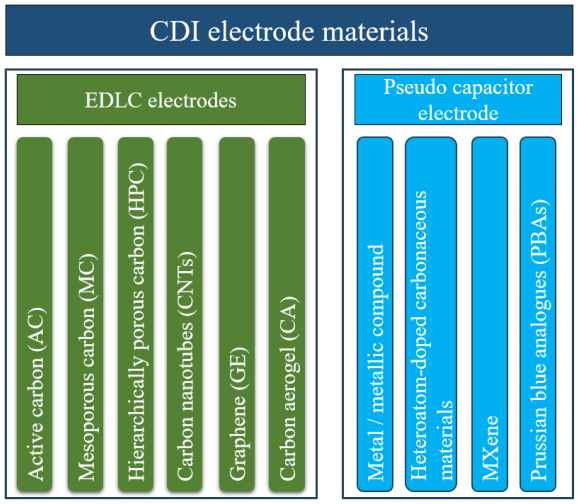


Figure 5. Summary of CDI electrode materials for environmental applications

2.4. Performance metrics

a. Maximum salt adsorption capacity

The salt adsorption capacity (SAC) in CDI gauges the system's ability to adsorb salt ions during its charge-discharge cycle. This cycle varies in duration, from brief periods with minimal adsorption to longer cycles reaching equilibrium. The maximum SAC (mSAC or eqSAC) is determined during extended cycles, where equilibrium is achieved by maintaining a fixed cell voltage until charging completes, ensuring constant salt concentration. Equilibrium occurs when the cell effluent's conductivity stabilizes. Calculating salt removal from feed water can be done via the single pass method (integrating the concentration difference over time) or the batch mode method (multiplying total solution volume by salt concentration decrease). Reporting SAC and mSAC involves dividing the removed salt mass by a representative electrode mass (in units of mg g^{-1}), often encompassing all solid components, not just the active ingredient (e.g., porous carbon). Authors should specify if SAC values consider total electrode mass or the active component, as non-active components can make up 5–15%

of the total mass. Gravimetric mSAC is common, but volumetric mSAC can offer further insights into electrode performance [1]. The SAC of the CDI process can be calculated by Eq. (1).

$$\mathrm{SAC} = \frac{M_{NaCl} \times \varphi \times \int_0^{t_c} (C_0 - C_t)dt}{m_e} \tag{1}$$

b. Average salt adsorption rate (ASAR)

The average salt adsorption rate (ASAR) is a key metric in evaluating CDI performance, complementing the information provided by the modified salt adsorption capacity (mSAC). While mSAC indicates the potential salt sorption capacity of CDI electrodes, ASAR focuses on the rate of salt sorption, expressed in mg g^{-1} min^{-1}. ASAR is influenced by various operational parameters, including charging time and feed salinity. Shorter charging times and higher feed salinities generally result in higher ASAR. Cell architecture also plays a role, with flow-through electrode systems often yielding higher ASAR compared to flow-by systems. The type of electrode material introduces complexities, as electrodes with sub-nanometer micropores may facilitate high salt sorption but encounter kinetic limitations. Electrode thickness and other factors like cell compression and macroporosity also impact ASAR. Optimal electrode compression during preparation is crucial for maximizing ASAR [28]. The ASAR of the CDI process can be calculated by (Eq. (2)).

$$\mathrm{ASAR} = \frac{SAC}{t_c} \tag{2}$$

c. Charge efficiency

Charge efficiency (CE), a pivotal metric in CDI technology, gauges how effectively electrodes charge and discharge. Calculated by dividing the accumulated electric charge by Faraday's number (F = 96,485 C mol^{-1}), it's then compared to the measured salt adsorption per cycle (Eq. (3)). This CE ratio signifies the adsorbed salt over charge and is crucial in assessing entire CDI cycles. It must remain below unity, though it can approach it. Influenced by cell voltage and feed water salt concentration, higher voltages and lower concentrations tend to increase CE. Its significance lies in determining energy consumption and validating equilibrium electric double layer (EDL) models for stable cycle predictions [1].

$$\mathrm{CE} = \frac{F \times \xi \times \varphi \times \int_0^{t_c} (C_0 - C_t)dt}{\int_0^{t_c} idt} \times 100\% \tag{3}$$

d. Energy consumption

Molar energy consumption (E_m) in CDI technology is a key metric used to quantify the energy efficiency of the CDI process concerning the removal of ions from a solution. This parameter is derived by dividing the total energy consumption during a CDI cycle by the moles of ions removed from the solution (Eq. (4)). In essence, it provides insight into the amount of energy required to achieve a specific ion removal capacity. Similarly, volumetric energy consumption (E_v) in CDI refers to another crucial metric that assesses the energy efficiency of the process, but with a focus on the volume of the solution treated. E_v is calculated by dividing the total energy consumption during a CDI cycle by the volume of the solution processed (Eq. (5)). This metric offers a perspective on the energy efficiency concerning the treated solution's volume. Both E_m and E_v play pivotal roles in evaluating

the performance of CDI cells. A lower E_m indicates a more energy-efficient ion removal process, while a lower E_v signifies higher energy efficiency in treating larger solution volumes [29].

$$E_m = \frac{\int_0^{t_c} (i \times V)dt}{\varphi \times \int_0^{t_c} (C_0 - C_t)dt} \tag{4}$$

$$E_v = \frac{\int_0^{t_c} (i \times V)dt}{V_{NaCl}} \tag{5}$$

where M_{NaCl} (g mole^{-1}), ϕ (L min^{-1}) and t_c (min) are the molecular weight of NaCl, operating flow rate and charging time, respectively; C (mM) and C_t (mM) are the initial and instant NaCl concentrations, respectively, which were calculated according to the EC value; m_e (g), F (C(mole e$^-$)$^{-1}$), and ξ (1 mole e−/mole NaCl) are the activated carbon mass coated on the electrodes, Faraday constant and stoichiometric number of ions, respectively; i (A), V (V) and V_{NaCl} (m^3) are the current, supplied voltage and solution volume during the charging period, respectively. The variables $C_{0,i}$, $C_{t,i}$, $C_{0,j}$, and $C_{0,j}$ represent the influent and effluent concentrations of ions i and j, respectively.

2.5. Operational considerations

a. Fluid flow designs

In the realm of CDI and MCDI research, two primary fluid flow designs prevail: batch mode and single-pass mode. Batch mode involves water sourced from a small container, with effluent returning to the feeding reservoir for conductivity measurement. As adsorption occurs, conductivity steadily declines until reaching a low, constant level, signaling electrode saturation. Conversely, single-pass mode utilizes water from a larger container, with treated water measured directly at the exit of the CDI unit. Here, effluent conductivity drops rapidly upon charging, gradually rising back to the inlet value. While batch mode is simpler, single-pass mode is more prevalent and efficient in practice due to its one-time passage of treated water through the CDI device, unlike the multiple recycles required in batch mode [8].

b. Operational parameters

The salt adsorption capacity in CDI is intricately influenced by several operation parameters. These include the current density, applied voltage, salt concentration, and flow rate. (1) Current density: Increasing the current density intensifies the electrochemical reactions occurring at the electrodes, thereby enhancing ion removal. However, excessively high current densities might lead to higher energy consumption, heat generation, and electrode degradation, compromising the system's long-term efficiency. (2) Applied voltage: Higher applied voltages create a stronger electric field, which enhances ion migration and consequently increases salt adsorption. However, elevated voltages can also cause issues like electrode fouling, gas evolution, and increased energy consumption, necessitating a balance between efficiency and system stability. (3) Salt concentration: A higher initial salt concentration in the feedwater results in a greater driving force for ion migration and adsorption onto the electrodes, thereby increasing salt removal efficiency. However, extremely high concentrations might cause saturation effects, limiting further adsorption and potentially leading to diminishing returns. (4) Flow rate: Flow rate impacts the contact time between the electrolyte and electrodes. Slower flow rates allow for longer interaction times, enabling better ion adsorption. Conversely, higher flow rates facilitate increased throughput but might limit ion-electrode interaction time, potentially reducing the overall salt adsorption capacity [8].

c. Operational issues

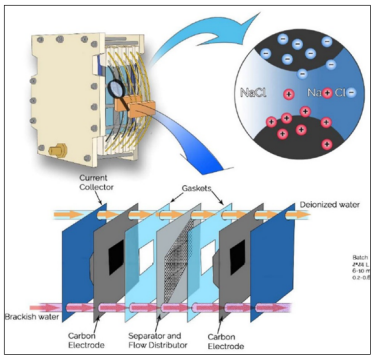
Operational challenges in CDI include addressing key facets for effective deployment. One significant issue is the risk of performance degradation due to fouling or scaling on electrode surfaces, hindering ion adsorption and capacitive efficiency over time. Long-term MCDI performance investigations amid organic matter revealed insights into fouling mechanisms and energy efficiency. Chen et al.'s study showed diminished salinity removal and increased energy consumption due to organic fouling on ion-exchange membranes and carbon electrodes, posing a challenge for efficient desorption during regeneration cycles and hampering demineralized water production. The study emphasizes the importance of pretreatment to mitigate organic matter, ensuring sustainable MCDI operation [30]. Mossad et al. conducted a pioneering study on fouling, scaling, and cleaning in CDI using activated carbon electrodes. Higher concentrations of total organic carbon (TOC) in the CDI feed solution led to reduced salt removal efficiency, lower production rates, and increased energy consumption. Electrode fouling, mainly from dissolved organic matter, clogged activated carbon pores, reducing electrosorption capacitance. While Ca and Mg minimally impacted CDI performance, Fe had a more significant effect on electrode fouling. Alkaline and acid cleaning solutions successfully restored CDI performance post-fouling, and pre-treatment to lower dissolved organic matter levels is recommended for sustained treatment efficiency [31].

Strategies to mitigate these concerns involve employing appropriate electrode materials, surface modifications, and periodic cleaning or regeneration protocols to maintain optimal performance. Additionally, ensuring consistent and stable electrical conductivity throughout the system, managing energy consumption, and optimizing flow dynamics within the electrodes are critical factors in addressing operational challenges. Employing advanced monitoring and control systems to detect and manage variations in feedwater quality or operating conditions can further enhance the resilience of CDI systems for real-world applications. Ultimately, a comprehensive approach combining material innovation, maintenance protocols, and advanced control mechanisms holds promise in effectively managing operational issues and maximizing the potential of capacitive deionization technologies. Notable, addressing the prolonged operational challenge involves a systematic approach using periodic acid and alkaline solutions to cleanse the system. The acid solution efficiently removes residual inorganic salts adhering to the CDI electrodes, while the alkaline solution aids in restoring any accumulated organic matter [32].

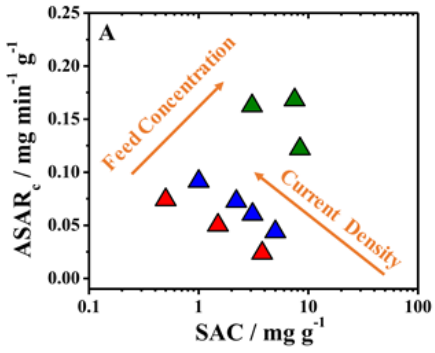
3. The real-world environmental applications of CDI

3.1. CDI for desalination applications

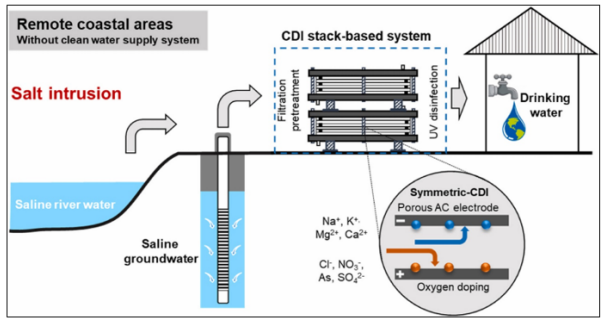
CDI has emerged as a groundbreaking technology with significant real-world applications in the field of desalination, responding effectively to the ever-increasing global demand for freshwater resources [2, 33]. In recent reports, CDI has demonstrated its practical utility by leveraging electrochemical principles to extract ions from saline water, offering a viable and sustainable alternative to conventional desalination methods. The deployment of CDI in desalination systems has yielded tangible results, showcasing its efficiency in reducing water salinity. The use of electrodes with high surface area and a porous structure allows CDI to selectively capture ions, resulting in a cost-effective and environmentally friendly approach that minimizes the energy requirements associated with traditional desalination processes. Real-world applications of CDI extend to diverse water treatment scenarios, making it a versatile solution applicable to both industrial and domestic settings. As evidenced in previous reports (Table 1), CDI's adaptability and efficiency underscore its potential to address global water scarcity challenges, presenting itself as a transformative force in the landscape of desalination technologies.



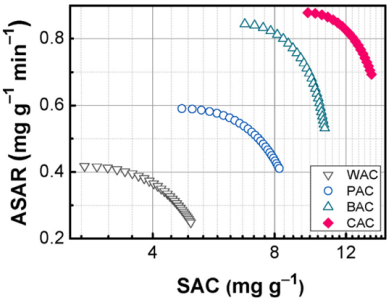
(a) 9-cell CDI stack for desalination



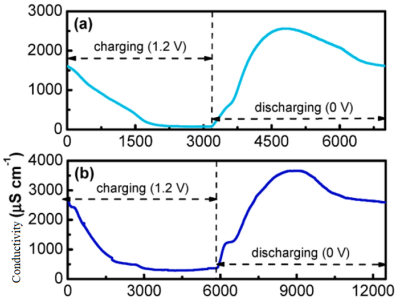
(b) SAC and ASAR plot



(c) 40-pair CDI stack for desalination



(d) SAC and ASAR plot



(e) The change of conductivity

(f) CDI desalination plant with a capacity of 60,000 m^3 day^{-1}

(g) CDI desalination plant with a capacity of 5,000 m^3 day^{-1}

Figure 6. Several real-world applications of CDI for desalination (reproduced with permission) [1, 7, 16]

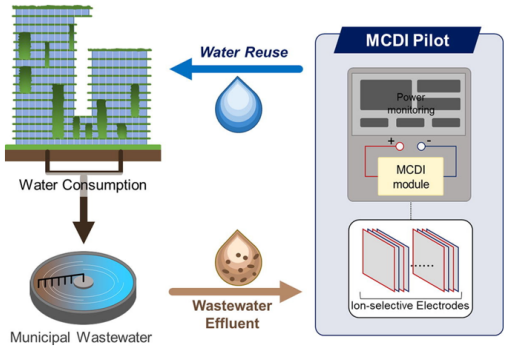
For example, Lado et al. conducted an extensive analysis of a CDI prototype featuring electrodes made of 3D graphite felt (Fig. 6(a)). The study showcased a 9-cell CDI stack subjected to 350 galvanostatic cycles (equivalent to 700 h of continuous operation), revealing remarkable stability in performance. The system achieved a good SAC and ASAR of approximately 8.2 mg g^{-1} and 0.18 mg g^{-1} min^{-1}, respectively (Fig. 6(b)). Noteworthy findings include energy consumption levels consistently below 200 Wh m^{-3} during single-pass experiments, which slightly escalated to 600 Wh m^{-3} in batch tests. It is worth noting that the implementation of an energy recovery system demonstrated the potential to decrease these values by an average of 40–50% [16]. In contrast to prior research, our study focused on utilizing a commercial coconut shell-derived electrode (CAC) in a CDI stack for treating saline water in remote coastal areas (Fig. 6(c)–(e)). The laboratory-scale CDI cell demonstrated high SAC (14.95 mg g^{-1}), rapid ASAR 0.87 mg g^{-1} min^{-1} and low energy requirements (0.088 kWh m^{-3}). Upscaling to a 40-pair CDI stack showed impressive performance in desalination across different water sources, achieving 98.4% Na^+ and 96.9% Cl^- removal. Notably, the system also exhibited a 97.6% reduction in $CaCO_3$ hardness, highlighting its adaptability and effectiveness for diverse water treatment scenarios [7]. On the other hand, our research introduces a novel approach utilizing nickel hexacyanoferrate (NiHCF) combined with reduced graphene oxide (rGO) as a high-performance pseudocapacitive intercalation cathode in HCDI for desalination. The NiHCF@rGO-assembled ACDI, operating at 1.2 V, demonstrates impressive performance with a salt adsorption capacity of 80.2 mg g^{-1}, a charge efficiency of 86.6%, and an energy consumption of 0.053 kWh m^{-3} when desalting a 4 g L^{-1} NaCl solution. Notably, it outperforms activated carbon-MCDI. The incorporation of rGO enhances the salt adsorption capacity of NiHCF by 27.7%, attributed to improved particle distribution and conductivity, resulting in lower charge transfer resistance and enhanced ion transport [10].

Notably, EST Water & Technologies in China specializes in the development of expansive CDI systems designed for desalination. These systems have diverse applications across multiple industries, such as a desalination plant for municipal wastewater reuse with a capacity of 60,000 m^3 day^{-1} (Fig. 6(f)), and a coal mine wastewater remediation plant with a daily capacity of 5,000 m^3 day^{-1} (Fig. 6(g)). These systems find utility in municipal groundwater, the petrochemical sector, steel mills, thermoelectric power plants, coal chemical manufacturing, paper mills, fertilizer production, and the treatment of high fluorine and high arsenic brackish water. With over 30 industrial systems already operational in China, the majority of these installations cater to the recovery and reuse of industrial and municipal wastewater. Treatment capacities range from 100 to 2000 m^3 h^{-1}. Notably, EST CDI modules demonstrate compelling energy efficiency, with energy consumption values approximately at 1.0 kWh m^{-3}, contrasting favorably with RO modules, which consume around 1.5 kWh m^{-3} [1]. The analysis of data alongside Table 1 underscores the significant potential of CDI technology in treating saline water, showcasing its viability even for large-scale treatment spanning tens of thousands of cubic meters per day. Our research aligns with findings from other research groups, confirming the consistency in desalination performance and energy consumption. Notably, the utilization of pseudocapacitor electrode materials demonstrates markedly enhanced desalination capabilities in contrast to conventional carbon materials. This advancement hints at the promising suitability of these materials for upcoming seawater treatment methodologies.

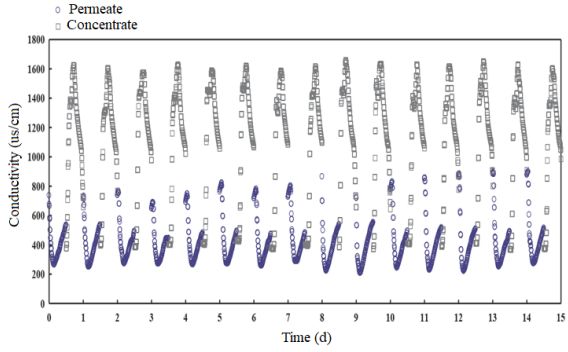
3.2. CDI for wastewater treatment and reclamation

The utilization of CDI in wastewater treatment and reclamation represents a cutting-edge solution with substantial potential to alleviate the global water scarcity crisis. The field of wastewater reuse is receiving more and more attention in the context of water scarcity and environmental pollution (Table 1) [13, 34]. CDI operates through the electrostatic adsorption of ions onto porous electrodes,

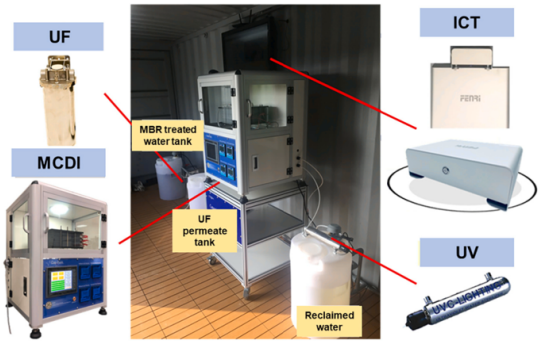
offering an environmentally friendly and energy-efficient alternative to traditional water purification methods. This technology's adaptability enables the removal of diverse contaminants, encompassing heavy metals, organic compounds, and salts, thereby contributing to the production of treated water of exceptional quality [2]. Moreover, CDI's reversibility makes it particularly well-suited for water reclamation, as the captured ions can be released during the regeneration process, prolonging electrode lifespan and minimizing waste production. Nevertheless, challenges like scaling and electrode fouling necessitate further attention for the widespread implementation of CDI in wastewater treatment and reclamation. Despite these hurdles, ongoing research and development in this domain hold significant promise, propelling sustainable water management practices and fortifying the foundation for a more robust and efficient water reuse infrastructure [27].



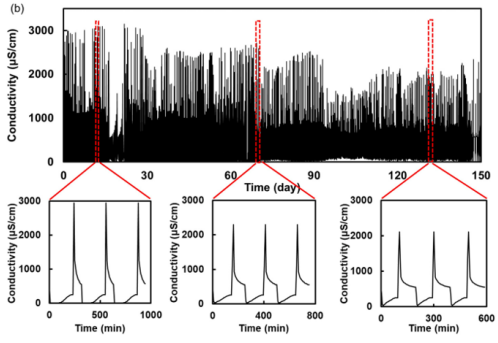
(a) MCDI pilot for wastewater reuse [34]



(b) 15 days of charging-discharging cycles [34]



(c) MCDI pilot for the domestic wastewater reuse [32]



(d) 5 months of charging-discharging cycles [32]

Figure 7. Applications of MCDI pilots for water reclamation in domestic wastewater treatment (reproduced with permission) [32, 34]

In a previous study, Kim et al. delved into the realm of MCDI on a pilot scale, employing ion-selective polymer-coated carbon electrodes to address wastewater reuse challenges (Fig. 7(a)). The pilot-scale MCDI setup comprised 50 pairs of meticulously designed anion- and cation-selective electrodes. Notably, their investigation yielded impressive results in terms of ion removal efficiency, particularly in tackling problematic charged impurities like nitrate (NO_3^-), with an outstanding removal rate of up to 91.08%. The study further demonstrated the efficacy of enhancing NO_3^- selectivity by manipulating operational parameters, emphasizing the positive impact of increased flow rates and reduced applied potential on water quality improvement. Intriguingly, a 15-day operational period (Fig. 7(b)) showcased robust reproducibility in electrosorption and regeneration processes for the

specially coated electrodes, even when faced with high concentrations of organics (12.4 mg L^{-1} of dissolved organic carbon) present in the wastewater feed solution. This research not only expands our understanding of MCDI but also underscores its potential as a sustainable and reproducible technology for wastewater treatment [34].

Shen et al. undertook the upscaling of a MCDI stack, showcasing its viability for the reclamation of domestic wastewater in industrial settings (Fig. 7(c)). The investigation delved into the desalination performance of the pilot-scale MCDI, focusing on critical parameters such as water quality, ion selectivity, water productivity, and fouling/scaling phenomena. Comprising 40 pairs of 20 cm × 20 cm activated carbon electrodes, the MCDI stack operated efficiently in a single-pass mode. Noteworthy achievements included substantial removal efficiency for ions in the wastewater effluent, with notable percentages observed for Ca^{2+} (up to 94%) and $NO_3{}^-$ (84%). The regeneration process, employing pump-off operation, significantly enhanced water recovery, reaching an impressive 75%. The MCDI-treated effluents consistently met industrial reuse standards, boasting an average conductivity of 103 μS cm^{-1}. Electrosorption selectivity analysis revealed a preference for cations, particularly Ca^{2+} and Mg^{2+}, owing to their high charge, while $NO_3{}^-$ exhibited the highest electrosorption selectivity among anions due to its hydration ratio. Importantly, the stability of water quality persisted over 5 months of consecutive charging-discharging cycles (Fig. 7(d)), underscoring the reliability of MCDI technology. These findings not only contribute crucial insights for the scaled-up implementation of MCDI stacks but also serve as a valuable reference point for advancing water reclamation efforts [32].

3.3. CDI for removal of other inorganic pollutants

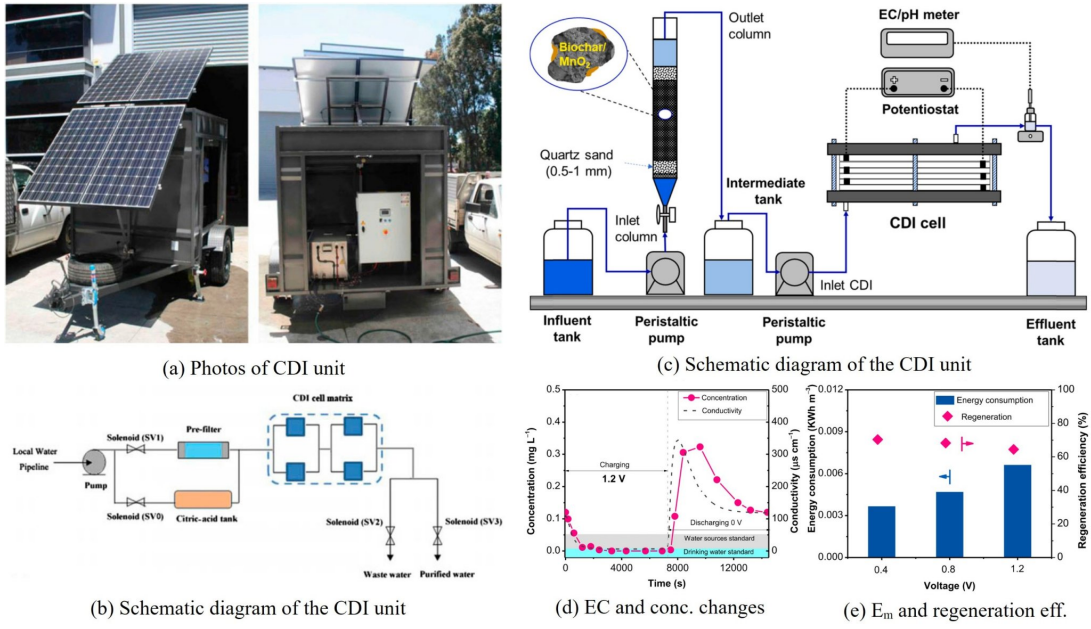
a. Heavy metal treatment

The presence of heavy metal ions in wastewater poses significant health and environmental concerns. These non-degradable elements, including arsenic, lead, mercury, cadmium, copper, nickel, and zinc, often accumulate in living organisms, leading to serious health disorders when concentrations exceed permissible limits. Industrial wastewater, originating from metal finishing, plating factories, semiconductor manufacturing, textile production, and landfills, is a primary source of these toxic metals. CDI has emerged as a promising solution, leveraging electrostatic interactions to remove hazardous metals [35]. Beyond removal, CDI facilitates the straightforward regeneration of these metals, offering a practical and sustainable approach to address heavy metal contamination in wastewater. The appeal lies in its potential for simple metal recovery, aligning with both environmental and economic considerations.

Zhang et al. introduced an innovative approach utilizing solar-powered CDI as a promising method for arsenic elimination from water sources (Fig. 8(a) and (b)). Their study demonstrated the efficacy and dependability of CDI technology in effectively reducing arsenic levels. Compliance with WHO's stringent arsenic guidance value (< 0.01 mg L^{-1}) was consistently achieved, showcasing removal rates exceeding 80% across various experimental setups. The favorable conditions for CDI-mediated removal of arsenate ions typically involve higher pH levels and lower salinity environments [35]. Fan et al. introduced a single-pass-mode CDI system tailored to combat arsenic contamination amidst various ions in groundwater. Operating at 1.2 V with six sets of 20 × 30 cm^2 activated carbon electrodes, this setup remarkably achieved an output arsenic concentration of 0.03 mg L^{-1} during charging, surpassing stringent Taiwan standards for drinking water and irrigation. The study also explored the system's efficacy in concurrent removal of coexisting ions, revealing their significant influence on arsenic extraction. Electrosorption analysis highlighted the hierarchy of anion removal preference: $NO_3{}^- > SO4^{2-} > F^- > Cl^- >$ As [36]. Fan et al. highlighted the differential sorption capacities in the

treatment of As(V) and As(III), attributing the superior sorption capacity for As(V) to its prevailing negative charge, as opposed to the non-charged nature of As(III) [37].

To overcome the limitation in As(III) removal, our group devised an innovative dual-stage system to combat arsenic contamination in groundwater. The system integrated an active manganese dioxide-rice husk biochar composite (active BC) filter and a single-pass-mode CDI system (Fig. 8(c)). The key issue in our system was that the active BC filter effectively oxidized As(III) to As(V) and removed both forms from the groundwater, which initially contained 0.94 mg L^{-1} arsenic (66.3% As(III) and 33.7% As(V)). The active BC filter, exhibiting specificity for arsenic removal, reduced the concentration to 0.12 mg L^{-1}. Subsequently, the single-pass-mode CDI system further enhanced arsenic removal, operating with a charging step at 1.2 V and discharging steps at 0 V. After a 2-hour operation, the average arsenic concentration in the treated tank of the 3-pair CDI system reached 0.008 mg L^{-1} (Fig. 8(d)), meeting WHO drinking water quality guidelines. The CDI-based system also achieved a low energy consumption of 0.0066 kW h m^{-3} (Fig. 8(e)) Our integrated filtration and electrosorption processes showcase the unique functionality of the active BC filter, demonstrating the dual-stage system's efficacy in real-world groundwater arsenic remediation [38].



(a) Photos of CDI unit

(b) Schematic diagram of the CDI unit

(c) Schematic diagram of the CDI unit

(d) EC and conc. changes

(e) E_m and regeneration eff.

Figure 8. Applications of CDI in removing arsenic from actual groundwater (reproduced with permission) [35, 38]

b. Hardness treatment

The quest for effective water softening methods amidst escalating scaling issues in industrial systems has led to the exploration of CDI as a promising alternative. Traditional methods like chemical precipitation, ion exchange, and membrane processes have presented drawbacks such as high energy consumption or excessive chemical usage. The inherent principle of CDI, leveraging electrical potential differences, offers a novel approach. Its unique ability to target multivalent ions like calcium and magnesium through intensified attraction to electrodes underscores its potential for water softening. Recent endeavors in harnessing and refining CDI technology for this purpose are documented in Table 1. However, despite its promise, challenges persist in optimizing CDI's efficiency, scalability, and cost-effectiveness for widespread adoption in mitigating water hardness [39].

Shen et al. highlighted the efficacy of MCDI pilot systems in treating domestic wastewater for industrial use, demonstrating a notable 94% removal of Na^{2+} and effective hardness reduction. Their findings underscored the favorable electrosorption selectivity of Na^{2+} and Mg^{2+} owing to their higher charge [32]. Additionally, Lee et al. echoed similar results concerning the hardness treatment efficiency of MCDI pilots in reclaiming domestic wastewater effluents. They observed a substantial reduction in water hardness, primarily attributed to multivalent cations like Na^{2+} and Mg^{2+}, with levels decreasing from 118.2 to 9.3 mg L^{-1} as calcium carbonate ($CaCO_3$) [13]. Notably, B. van Limpt, A. van der Wal determined the water and chemical savings that can be achieved in a cooling tower by desalinating and softening the feed water stream with a full-scale MCDI system. By monitoring the water use of the cooling tower, and comparing this to a scenario without MCDI, chemical savings up to 85% could be achieved. Additionally, water savings up to 28%, and waste water savings up to 48% could be achieved. MCDI energy use for desalination of cooling tower feed water was between 0.1 and 0.2 kWh m^{-3}. Preferential uptake of chloride and calcium was observed, which lowers the risk of scaling and corrosion in the cooling tower and allows for further chemical and water savings [40]. Chen et al. introduced a MCDI system for effective treatment of various water typessoft tap water (T1), hard tap water (T2), cooling tower blowdown (W1), and industrial wastewaterwith consistent removal rates of at least 70.8% for hardness and 51.9% for conductivity. Ion removal selectivity varied based on initial ion concentrations, favoring Na^{+} for T1, W1, and W2, and Na^{2+} for T2. The system demonstrated high charge efficiency and low energy consumption, requiring 0.014 to 0.68 kWh m^{-3} at 1.6 V, maintaining a charge efficiency over 70% [41].

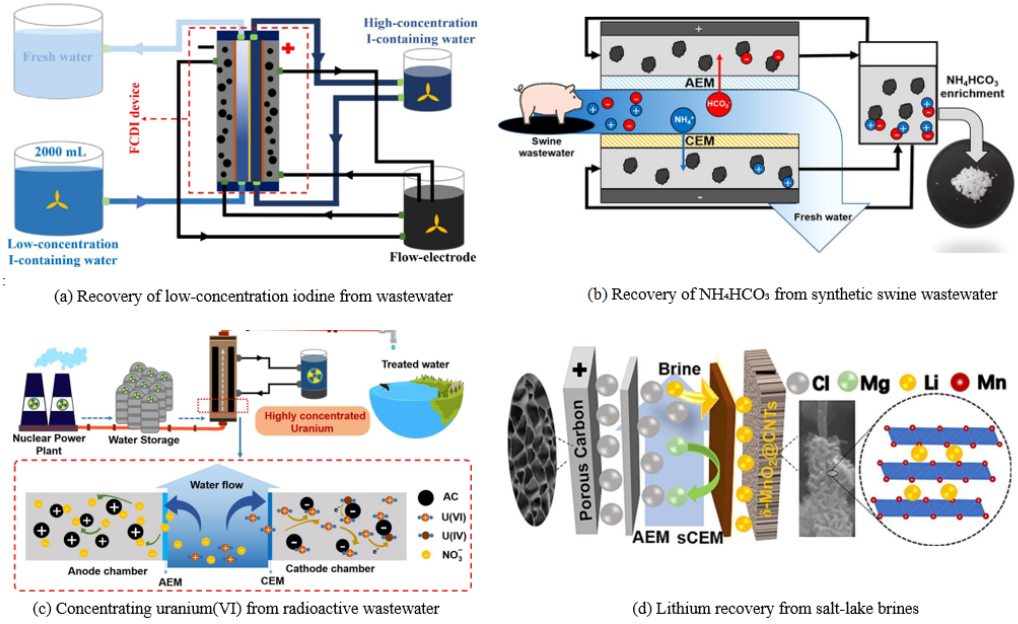
In our previous studies, hierarchical porous carbon (HPC) from tailored activated rice husk biochar can provide a new opportunity to achieve not only high-performance electrosorption but also for hardness treatment in single-pass capacitive deionization. In details, the HPC electrode showed good regeneration ability in consecutive cycles for the removal of inorganic pollutants, i.e., NH_4^{+}, Mg^{2+} and Cu^{2+}, with electrosorption capacities of 1.54, 1.53 and 0.52 mg g^{-1}, respectively [18]. In other our study, a 40-pair CDI stack was applied for saline hard groundwater in a remote coastal area in Vietnam. The hardness was reduced from 457.05 to 11.01 mg L^{-1} as $CaCO_3$, achieved 97.6% efficiency [7]. The achieved high efficiency of hardness removal is most likely due to the highly porous oxygen-doped carbon electrodes, in which 3D pore channel networks facilitating ion transport and functional groups providing abundant active sites for ion attraction Water hardness poses a persistent challenge in various treatment methods like ion exchange, membrane filtration, and chemical processes due to the propensity of hard ions to cause clogging and scaling issues. This creates inefficiencies and often incurs substantial costs, particularly in domestic settings. However, recent findings from our research group, along with insights from other studies, highlight the efficacy of CDI technology in addressing this issue. Our collective research indicates that CDI stands out as a viable solution for water treatment, especially in cases of high hardness levels (up to 500-600 mg L^{-1}). What's more, it demonstrates a remarkable ability to sustain stable operation over extended periods, ranging from several months to years, given proper maintenance and full operational implementation.

3.4. CDI for resource recovery

CDI stands as a promising solution for resource recovery from various sources like wastewater, groundwater and seawater. Its application extends beyond desalination to the retrieval of valuable resources like ammonium [42], phosphorous [43], uranium [15], iodine [44] and lithium [45]. The necessity for sustainable resource management has driven research and development in CDI, aiming to harness its capabilities for multifaceted resource recovery. Current endeavors highlight successful extraction processes for certain elements, showcasing the potential for broader application. However,

challenges persist in achieving efficient and selective recovery while maintaining cost-effectiveness. Optimizing electrode materials, enhancing selectivity, scaling up processes, and minimizing energy consumption are among the primary hurdles yet to be fully addressed. Additionally, exploring the extraction potential of other resources and advancing the understanding of CDI's broader applications remain crucial for its widespread adoption and impactful utilization.

Iodine, a crucial yet limited resource, holds significance as a vital trace element for the human body. Research by Liu et al. delved into the utilization of FCDI technology for the sustainable extraction and recovery of low-concentration iodine from wastewater (Fig. 9(a)). Their findings showcased a consistent iodine removal efficiency exceeding 96% over 100 cycles, demonstrating the FCDI unit's effectiveness under optimized operational parameters. Extended batch experiments revealed the capacity to concentrate a low-concentration iodine solution (100 mg L^{-1}) by 18-fold within 24 hours, resulting in a drop to 8.2 mg L^{-1} in the feed water chamber and a rise to 1818.5 mg L^{-1} in the concentration chamber [44]. Han et al. introduced a novel FCDI system tailored for effective removal of bicarbonate ions (HCO_3^-) and enrichment of ammonium bicarbonate (NH_4HCO_3) from synthetic swine wastewater (Fig. 9(b)). Their findings demonstrated the production of a concentrated NH_4HCO_3 solution at 1.61 M with 97.2% purity within a 30 h timeframe. The system exhibited a carbon removal rate of 1.01 kg C m^{-2} d^{-1} while consuming 2.87 kWh kg^{-1} C of energy [46].



(a) Recovery of low-concentration iodine from wastewater

(b) Recovery of NH_4HCO_3 from synthetic swine wastewater

(c) Concentrating uranium(VI) from radioactive wastewater

(d) Lithium recovery from salt-lake brines

Figure 9. Applications of CDI in resource recovery from water and wastewater (reproduced with permission) [15, 44–46]

Addressing the global challenge of treating large volumes of low-concentration radioactive wastewater, Zhou et al. explored the efficacy of FCDI as an innovative electrochemical method for concentrating radioactive wastewater (Fig. 9(c)). Their studies demonstrated consistent removal rates, maintaining uranium removal above 99% across multiple cycles. Through long-term batch experiments, they achieved a 47-fold concentration increase of the initial 60 mg L^{-1} uranium feedwater, resulting in a final electrolyte concentration of 2843 mg L^{-1} uranium and a remarkable volume reduction from 2400 mL to 40 mL. Optimized conditions yielded an 86% charge efficiency alongside a low

energy consumption of 2.03 mg J^{-1} [15]. Addressing the pressing need for efficient lithium recovery from salt-lake brines, Si et al. introduced a MCDI system designed for this purpose (Fig. 9(d)). Utilizing δ-MnO_2-x@CNTs, they achieved a notable lithium recovery capacity of 43.0 mg g^{-1} with a corresponding rate of 5.17 mg g^{-1} min^{-1}. Remarkably, in scenarios where Li and Mg concentrations escalated to 2420 and 26487 mg L^{-1} (Mg/Li mass ratio = 10.9), the system exhibited enhanced recovery capacities: 121.3 mg g^{-1} for lithium and 204.6 mg g^{-1} for magnesium. Consequently, the Mg/Li mass ratio decreased to 2.33 in the recovery solution [45].

Table 1. Applications in real life conditions of CDI systems for various purposes

#	CDI type	Electrode	Flow mode	Application	SAC (mg g^{-1}) and/or efficiency (%)	Energy demand	Ref.
				CDI for desalination application			
1	9-Cell CDI stack	3D graphite felt, 300 cm^2	Single-pass	Desalination	6.60 mg g^{-1} as NaCl	0.02 kWh m^{-3}	[16]
2	2 cell-CDI	Activated carbon cloth	Batch	Desalination	8.90 mg g^{-1} as NaCl	0.78 Wh m^{-3}	[33]
3	CDI-based system developed by EST Water & Technologies in China	Activated carbon	Single-pass	Desalination, offering versatile applications across various industries	-	1.00 kWh m^{-3}	[1]
4	40 pairs-CDI stack	Commercial coconut shell-derived electrode	Single-pass	Desalination, 98.4% Na^+, 96.9% Cl^-	14.9 mg g^{-1} as NaCl, 98.4% Na^+, 96.9% Cl^- removed	0.04 KWh mol^{-1} and 0.09 kWh m^{-3}	Our study [7]
				CDI for wastewater treatment and reclamation			
5	50 pairs-MCDI stack	Activated carbon electrodes coated by ion selective polymers	Single-pass	Reuse of municipal wastewater	3.58 mg g^{-1} as $NO_3{}^-$, 91.08% of $NO_3{}^-$ was removed	-	[34]
6	10 pairs-CDI stack	ACS20 activated carbon	Single-pass	Desalinating secondary effluent from a domestic wastewater treatment plant	9.07 mg g^{-1}, conductivity of the product water of 1.27 µS cm^{-1}	0.12 kWh m^{-3} and 0.03 KWh mol^{-1}	[13]
7	40 pairs-CDI stack	ACS20 activated carbon	Single-pass	Reuse of domestic wastewater, wastewater effluent	Up to 84% $NO_3{}^-$	-	[32]
8	200 pairs-CDI stack, dimension of 158 × 174 × 0.3 (mm)	coconut shell derived activated carbon	Single-pass	Removal of As	Effluent arsenic concentration of < 0.01 mg L^{-1}	-	[35]

#	CDI type	Electrode	Flow mode	Application	SAC (mg g^{-1}) and/or efficiency (%)	Energy demand	Ref.
9	6 pairs-CDI stack	F400 activated carbon	Single-pass	Removal of As	As* (0.002), Na^+ (2.558), Na^{2+} (0.483), effluent arsenic concentration of < 0.03 mg L^{-1}	0.50 kW h m^{-3}	[36]
10	3 pairs-CDI stack	ACS20 activated carbon	Single-pass	Removal of As	Effluent arsenic concentration of < 0.008 mg L^{-1}	0.07 kW h m^{-3}	Our study [38]
				CDI for hardness treatment			
11	MCDI-based system developed by the company Voltea B.V.	Activated carbon	Single-pass	Treating feed water of cooling towers facilities	-	0.10 and 0.20 kWh m^{-3}	[40]
12	40 pairs-CDI stack	ACS20 activated carbon	Single-pass	Reuse of domestic wastewater, wastewater effluent	4.4 mg g^{-1} as Mg^{2+} and 9.4 mg g^{-1} as Na^{2+}, up to 94% Na^{2+} removed	-	[32]
13	10 pairs-CDI stack	ACS20 activated carbon	Single-pass	Softening secondary effluent from a domestic wastewater treatment plant	Hardness reduced from 118.2 to 9.3 mg L^{-1} as $CaCO_3$	0.12 kWh m^{-3} and 0.03 KWh mol^{-1}	[13]
14	10 pairs-CDI stack	ACS20 activated carbon	Single-pass	Treatment of soft tap water, hard tap water, cooling tower blowdown	70.8% for hardness removed	0.01 to 0.68 kWh m^{-3}	[41]
15	CDI-based system	Hierarchical porous carbon (HPC) from tailored activated rice husk biochar	Single-pass	Softening synthetic hard water	1.53 mg g^{-1} as Mg^{2+}	-	[18]
16	40 pairs-CDI stack	Commercial coconut shell-derived electrode	Single-pass	Softening real saline hard water	1.22 mg g^{-1} as Na^{2+}, 97.6% hardness removed	0.09 kWh m^{-3}	Our study [7]
				CDI for resource recovery			
17	MCDI pilot	2-unit facility (15 pairs of electrodes per unit)	Batch	Ammonia removal from municipal wastewater	39.1% $NH4^-$, 47.6% Mg^{2+}, and 33.3% Na^{2+} removed	1.16 kWh m^{-3}	[42]
18	FCDI cell	2 Plexiglas plates (6 cm × 5 cm × 1 cm), 2 graphite plates with flow channels (6 cm × 5 cm),	Batch	Phosphate recovery from synthetic fermented broth	110.78 mg L^{-1} of P in the anode chamber	1.89 kWh kg^{-1} P	[43]

#	CDI type	Electrode	Flow mode	Application	SAC (mg g^{-1}) and/or efficiency (%)	Energy demand	Ref.
19	FCDI cell	Activated carbon + Carbon black	Batch	Recovery of iodine in saline wastewater	Iodine concentration increased from 100 to 1819 mg L^{-1} after 1000 cycles	-	[44]
20	FCDI cell	-	Batch	Ammonium bicarbonate (NH_4HCO_3) recovery	1.61 M of NH_4HCO_3 concentrated solution with 97.2% of purity	2.87 kWh $kg^{-1}C$ removed	[46]
21	MCDI cell	δ-MnO_2-x@CNTs	Batch	Li recovery from salt-lake brines	Li recovery capacity of 43.00 mg g^{-1}	-	[45]
22	FCDI cell	-	Batch	Uranium recovery from radioactive wastewater	Concentrate the feed water from 60 to 2843 mg L^{-1} U	2.03 mg J^{-1}	[15]

4. Challenges and future directions

In the realm of CDI, several challenges persist that must be addressed to facilitate its effective implementation in real-world applications. First and foremost, the energy efficiency and cost-effectiveness of CDI systems are areas of concern. High energy consumption can limit the practicality of CDI technology, particularly in large-scale applications. As such, future research should focus on methods to reduce energy requirements and operational costs, making CDI a more attractive solution for various sectors. Another critical challenge lies in the materials and electrode design. The choice of electrode materials, their structural design, and their overall durability significantly influence the performance and lifespan of CDI systems. Investigating advanced materials like carbon nanotubes and graphene, as well as innovations in electrode design, can lead to substantial improvements. Scaling up CDI for real-world applications is another hurdle. While CDI has shown promise in lab settings, translating this success to large-scale municipal or industrial water treatment remains a challenge. Researchers should explore strategies to make CDI more scalable and cost-effective for these broader applications.

Looking ahead, several promising directions for research and development can help overcome these challenges and drive the adoption of CDI technology. Advanced electrode materials and nanotechnology offer exciting possibilities to enhance CDI performance and durability. Additionally, improvements in energy storage and management systems can reduce energy consumption, making CDI more sustainable and cost-effective. Enhanced electrode design and 3D structures represent innovative pathways to boost ion adsorption and desorption rates, ultimately enhancing CDI efficiency. Moreover, the integration of CDI with other water treatment technologies and renewable energy sources is a promising avenue to explore, allowing for greater versatility and practicality. In envisioning the future, advanced modelling and machine learning applications can expedite design iterations and enhance CDI efficiency. Exploring emerging applications in remote or resource-constrained regions and establishing industry standards and policy frameworks will encourage wider adoption and ensure quality assurance across CDI implementations. Addressing these challenges and pursuing these future directions will unlock CDI's full potential, ushering in more efficient, sustainable, and widely applicable water treatment technologies. Lastly, collaboration among researchers from various disciplines, including materials science, electrochemistry, and environmental engineering, is essential to address CDI challenges comprehensively.

5. Conclusions

In conclusion, CDI emerges as a highly promising technology with significant implications for real-world environmental applications in water/wastewater treatment. Our comprehensive exploration of CDI's principles, configurations, performance metrics, and environmental considerations highlights its potential as a sustainable, efficient, and cost-effective solution. The in-depth analysis of CDI configurations and electrode materials underscores their direct impact on system efficiency and ion removal capacities. Importantly, the environmental perspective reveals CDI's reduced energy consumption, minimal chemical usage, and its potential to mitigate the environmental footprint of water treatment processes. The demonstrated efficacy of CDI in diverse applications, from desalination to the removal of inorganic pollutants and resource recovery, underscores its versatility and adaptability to real-world challenges. Moreover, our review emphasizes the necessity of addressing challenges such as scale-up, optimization, and ensuring long-term operational stability to unlock CDI's full potential. Looking ahead, the identified challenges present opportunities for innovation and advancement in CDI technology. Integrating these findings into future research and development efforts will facilitate the realization of CDI as a key player in sustainable water management strategies. Ultimately, CDI stands at the forefront of revolutionizing water treatment, offering a pathway to address pressing environmental concerns while paving the way for a more sustainable and responsible future in water purification and resource recovery.

Acknowledgments

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